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IMPROVING THE THERMAL METHOD FOR ASSESSING THE TECHNICAL CONDITION OF ROLLING BEARINGS BASED ON THE HEATING RATE CRITERION

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An improved method of passive thermal control has been proposed in order to operatively assess the technical condition of rolling bearings, based on studying the heating rate of a bearing. The values of the heating rate of ball, roller, and conical rolling bearings, as well as ball separators, have been determined empirically. It has been shown that the discrete limit heating rate values derived under the regular heating mode of mechanical reducers during stand tests are suitable for use as a diagnostic criterion for rolling bearings. Based on the heating speed criterion for mechanical reducers, it is possible to perform an operative assessment of the technical condition of rolling bearings of different types during the operation of equipment for different purposes. It has been established that for a rolling bearing in a working technical condition the heating rate under a regular heating mode does not exceed 1 °C/min. The resulting value corresponds to the diagnostic criterion for the heating rate of mechanical reducers in a working technical condition of $\vartheta_n \leq 1.1$ °C/min. Using a diagnostic parameter of the heating rate under a regular heating mode makes it possible to resolve the issue related to the duration of control over the technical condition of a rolling bearing using a thermal method. Reducing the control procedure duration, when using the improved thermal non-destructive testing, by 4 times, would yield a reduction in operating costs due to the possibility of ongoing control over rolling bearings at the beginning of the equipment operation. It has also been confirmed that the heating rate of rolling bearings under a regular heating mode directly depends on their technical condition and does not depend on the load transferred and the mode of operation of the bearing nodes of the technological equipment. The proposed method could be applied in the maintenance system based on the actual condition of the equipment for the operative control over rolling bearings

Keywords: non-destructive testing, rolling bearing, technical condition, heating rate, thermal method

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1. Introduction

The most common mechanical assembly of industrial equipment is the bearing node. The technical condition of the bearing node is mainly determined by the technical condition of the rolling bearings.

Finding the optimal method of diagnosing and monitoring the technical condition of industrial equipment is directly related to the safety of production. This leads to optimization of the cost of replenishing the technical resource of equipment, improved reliability, and reduced equipment downtime, which affects the cost of manufactured products.

The most popular method in the system of technical diagnosing is a non-destructive testing method, the development of which involves scientists all over the world [1]. Today we know many different types of the non-destructive testing of the technical condition of an object: acoustic; vibroacoustic; eddy current; magnetic; optical; using penetrating substances; radiation; radio wave; thermal; electric [2]. Each of these methods has its own scope and inherent disadvantages, which is why there is no universal method for the non-destructive testing of the technical condition of an object [3].

In addition to the issue of reliability of technical diagnosing, the problem of the effectiveness of the maintenance system at an enterprise is becoming more and more urgent. Reducing the cost of monitoring the technical condition of an object is provided by choosing the optimal control parameter and the means of measuring equipment, as well as an effective control method. Particular attention is paid to the non-destructive testing of rotating elements as a critical task in ensuring the reliability of production processes in all industries, as well as in connection with the increased safety requirements for manufactured products. Rolling bearings are important elements in the structure of machines and equipment that function in difficult atmospheric conditions under heavy loads. The performance of industrial equipment in general depends on their technical condition.

One of the important factors influencing the reliability of the bearing node is the quality of the current control over its technical condition during the operation of the equipment. For complex mechanisms, enterprises introduce input and current control systems for the technical condition of machines and mechanisms [4]. Maintenance systems are introduced into production to implement a smart factory within Industry 4.0 [5] and create standard fault diagnostic bases to avoid repeated failures [6].

In recent years, there has been an evolution of research into the thermal method of non-destructive testing [7]. The increase in the demand for the thermal method is due to the fact that any mechanical energy is always accompanied by the release of heat energy. Control over the heterogeneity of a thermal field is used to assess the technical condition of the controlled object. Any deviations in the values of the defining parameters of an object's current state from the nominal values of the parameters that determine the proper state of the object lead to a change in the temperature field [8].

The prospect of the thermal method of non-destructive testing is that there is no need to stop the functioning equipment for instrumental control. In addition, the affordability of technical equipment and the simplicity of the technical control methodology ensures that the reliability of the measurements obtained is acceptable for diagnosing.

To detect mechanical nodes' failures, the most common and most popular method of non-destructive testing is the passive method of thermal control. Many procedures of determining faults according to the criterion of the stabilized heating temperature of the object have been developed; the normalized values that correspond to the critical condition of the object have been derived; the thermal modes of mechanical nodes have been studied in detail.

The passive method of thermal control is based on the theory of thermal conductivity under the thermal stabilization mode, which requires a long time to get the object of control into control mode and is associated with energy costs. This feature of the passive method of thermal non-destructive testing does not make it possible to quickly assess the technical condition of an object. In addition, there is no single universal criterion for the working technical condition of mechanical equipment nodes based on the value of a surface heating temperature.

Thus, it is a relevant task to improve the thermal method for the non-destructive testing of machines and mechanisms, which requires further experimental research.

2. Literature review and problem statement

The transition of enterprises from routine maintenance to a condition-based maintenance system has led to an increase in the number of studies into the monitoring of the technical condition of rolling bearings.

However, despite the rapid development of the non-destructive testing methods for bearings, the most common and demanded one is thermal control based on the value of the working temperature of the surface of a bearing body under the mode of heating stabilization.

In contrast to vibrational methods, which are effective for detecting cracks and chipped in bearings, the thermal method is effective for detecting nascent deformations in bearings associated with lubricant disruption, assembly defects, and other non-physical damage [9].

Experimental studies of the temperature behavior of rolling bearings of different types under different conditions and modes of operation are extremely important for the development of technical control and for diagnosing bearing nodes based on the thermal method.

Infrared thermography is widely used as a tool to monitor the thermal condition of a controlled object, to detect the damage that leads to an increase in the heating temperature of the node [10]. The infrared thermographic method is applied to monitor and diagnose ball bearing malfunctions by quantifying and qualitatively assessing temperature characteristics [11].

An experimental study of the radial ball bearing reported in [12] has shown that the high viscosity of the oil, the speed of rotation, and the body cooling rate lead to a greater temperature gradient.

The thermal analysis of the rolling bearing in a conveyor belt at a coal mine under conditions of high loads and heavy pollution showed that pollution particles had much less impact on the bearing heating than installation defects. The inner ring of the working rolling bearing is heated more intensively to a maximum temperature of T_i=71.5±0.5 °C, while the outer ring is heated less intensely to a temperature of T_o=61.5±0.5 °C [13].

A study into the bearing heating, depending on the amount and size of the contaminants, has shown that, compared to the rated condition, the geometric dimensions of a foreign substance have a greater impact than its quantity [14].

A study of the effect of assembly quality on the thermal behavior of the rolling bearing in a spindle node has shown that the greater inclination angle of the outer bearing ring leads to greater heat-making power of the bearing and a higher heating temperature of the outer bearing ring, that is, to exceeding the rated temperature value [15].

A study of closed bearings [16] has shown a deterioration in the performance of the lubricating materials of the bearing during long-term storage for preservation, which leads to their premature wear when commissioned without pre-replacing the lubricant.

When studying the thermal sliding on the surface of the contact between the inner track of the ball bearing, the authors of [17] demonstrated that the friction moment, estimated taking into consideration the thermal effect, is higher than the torque estimated when ignoring the thermal effect.

A study of the thermal modes of mechanical objects [18] has shown that at constant loads and speeds of rotation the technical condition of the mechanisms is characterized by the patterns in heating temperatures. The three temporal heating phases correspond to a disordered regime, a regular regime, and the mode of heating stabilization. The intensity of temperature growth in a mechanism or node in a faulty technical condition is higher than that in a working condition. The authors established a limiting value for the rolling bearings' heating rate of ±0.5 °C/min under the mode of thermal stabilization. A study of the thermal mode of the sludge pump rolling bearings under production conditions has shown that changes in the heating temperature over time occur nonlinearly. The rate of change in the temperature of the rolling bearing in the working condition is 0.35 °C/min, which does not exceed the rated value of 0.5 °C/min under a thermal stabilization mode. A study of the defective states of a journal node has shown that the destruction of the frontal rolling bearing with the fallout of a first roller begins on minute 12 of the node operation. When the axial load is reduced, the increase in heating temperature slows down. When the load increases, the bearing is destroyed with the local heating of the rings, the release of smoke, and the fallout of the balls. In this case, the heating of the axle box body does not exceed the rated critical temperature of 120 °C. The bearing is destroyed on minute 20 of its operation.

The systematization of the results of the above studies has revealed that the current thermal method to control bearing nodes relies on the measurements of the discrete temperature values as a determining parameter for diagnosing the technical condition of the bearing under the heating stabilization mode, which is compared during the monitoring to the maximum allowable value set by the article's specifications.

The main drawback of the current thermal method of assessing the technical condition of rolling bearings is the slow reaction of the controlled parameter (heating temperature) to the detection of the defect. It takes a long time for an object to enter a temperature control mode to compare the resulting current values of the controlled parameter to their reference values. This is due to the physical patterns of heating solids, having three heating modes over time: disordered, regular, and temperature stabilization.

Modern requirements for the methods of technical diagnostics of mechanical equipment with bearing assemblies imply the task of developing up-to-date energy-efficient solutions, namely, to resolve the issue of inertia of the thermal method of non-destructive testing.

The heating stabilization mode of bearings is well studied. The end time of temperature stabilization and the rated critical surface temperature of different types of bearings are indicated in the industry instructions, testing procedures and technical control techniques, and the technological maps of equipment technical condition control. According to the standard DSTU IEC 60706-3:2008, the heating temperature of the bearing nodes is considered stable if the temperature difference over 4 hours does not exceed 2 °C.

The disordered regime stage is not suitable for diagnosing due to the large impact exerted by the initial heating conditions of the object. For operative technical control, the most suitable is the stage of regular heating, at which the function of heating temperature over time is exponentially dependent. However, so far not enough experimental studies have been conducted on the non-stationary heating of complex objects by a regular thermal regime method. The method is based on the study of the stage of regular heating independent of the original condition, shape, size, and homogeneity of the object [19, 20].

In bearing nodes, there are non-stationary processes with intensive thermal relations, the bearing operation is accompanied by the formation of an intense dynamic (changing in time and space) temperature field on the surface of the bearing body, whose characteristics depend on the type of bearing, the speed of rotation, the nature of the load, and the temperature conditions of operation, as well as the structure and technical condition of the bearing node. Therefore, it appears promising to study and improve the passive method of the thermal non-destructive testing of the technical condition of rolling bearings during testing and technical control based on the method of regular thermal heating.

A series of field experiments were conducted to study the thermal behavior of ball and conical rolling bearings under different testing regimes of the mechanical reducers in railroad passenger cars [18, 21–23]. The aim of the experimental research was to find the optimal solution to reduce the duration of control when testing reducers for the quality of assembly after repair. The studies have shown that the heating rate under a regular heating mode directly depends on the quality of the assembly of the bearing node. At a rotation frequency of 900 rpm and a transmitted load of 28, 32, and 40 kW, the heating rate of a workable bearing node under a regular heating mode does not exceed 1.1 °C/min (Fig. 1) [21]. The assembly-defective bearing nodes demonstrate, in the stage of a regular heating mode of the rolling bearings, the peak heating rate values exceeding 2 °C/min (Fig. 2) [22].

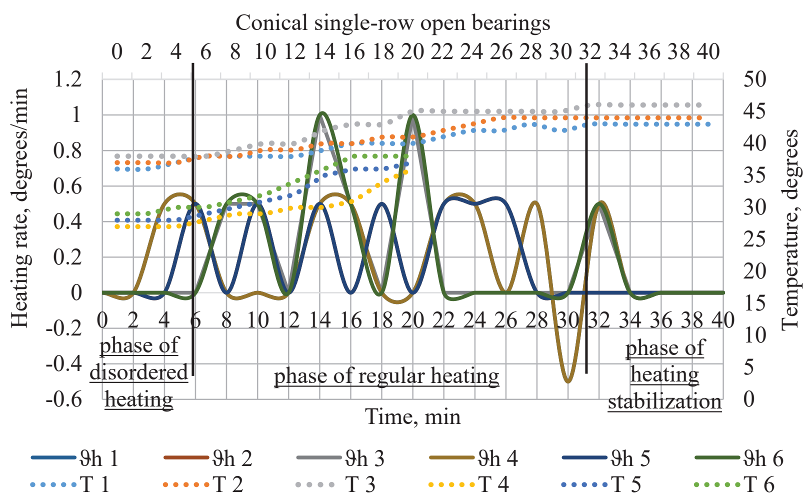


Fig. 1. The results of testing reducers in an efficient technical condition for the quality of assembly under a load of 28 kW: T – temperature bearings; θh – heating rate bearings

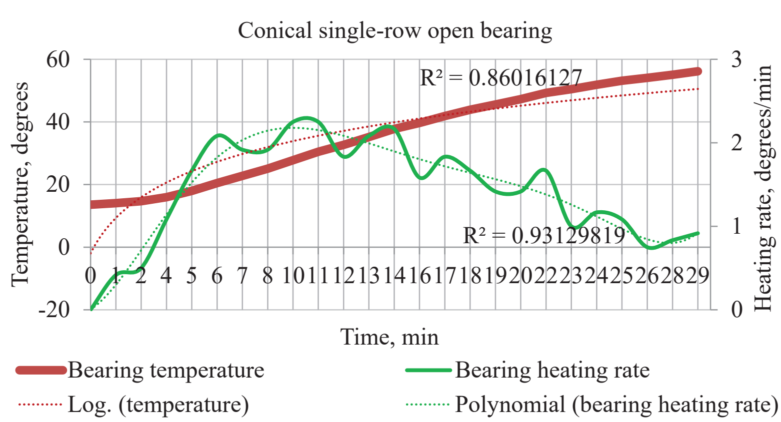


Fig. 2. The results of testing a load-free reducer with an assembly defect

Having studied the thermal behavior of rolling bearings, an improved method of the thermal control over the technical condition of the mechanical reducers in railroad passenger cars during bench tests was proposed. The method is based on determining the heating rate of a reducer body's surface at control points and assessing the technical condition of the rolling bearings based on the empirical value of the heating rate criterion under the regular heating mode of the bearings. The technique of the thermal diagnosing of mechanical reducers using the diagnostic criterion of heating rate is protected by the patent of Ukraine for a useful model [24]. The method of the thermal control of reducers based on the heating rate criterion was first verified at the passenger car depot of the Bakhmach station, the Regional Branch of the South-Western Railroad, the joint-stock company «Ukrainska zaliznytsya».

A study was carried out on the pattern of changes in the heating temperature of the rolling bearings in a screw-cutting lathe [25] and a vertical drilling machine during tests without load. It was confirmed that under a regular heating mode, the heating rate of the rolling bearings in a spindle assembly in an efficient technical condition does not exceed 1.1 °C/min.

The heating modes of friction units have been insufficiently studied for the technical control of bearing units by the method of the thermal non-destructive testing based on the method of regular thermal heating. Therefore, it is necessary to continue to study the pattern of heat distribution in the rolling bearings during the heating process as the most responsible element of bearing nodes.

3. The aim and objectives of the study

The aim of this study is to confirm the effectiveness of the practical application of the advanced passive thermal control method and operative assessment of the technical condition of the bearing nodes of mechanical equipment of various functionality whose structures include rolling bearings of different types. To accomplish the aim, the following tasks have been set:

– to assess the impact of the technical condition and the operational modes of rolling bearings of different types on the change in temperature and heating rate during equipment operation;

– to check the possibility of applying the empirical value of the heating rate criterion of mechanical reducers during bench tests as a diagnostic criterion for the operative assessment of the technical condition of rolling bearings of different types;

– to formulate the basic principles of the thermal method of assessing the technical condition of rolling bearings based on the criterion of a heating rate, taking into consideration the current requirements for the introduction of energy-efficient technologies based on the results of this research.

4. Materials and methods to study the heating of rolling bearings

Our experimental research was carried out using the technological equipment made by Blema in the canning shop No. 5 of the private joint-stock company «Production Association «Odesa Cannery» (Ukraine). We investigated bearings of different types under different speed, load, and temperature operational conditions. The temperature control of the bearing nodes of the press machine RKXD-63 was carried out, in the manufacture of whole-drawn can No. 3 and ScStrEO disk scissors for slicing the blanks of the tin case No. 5.

The values of the heating temperature of the bearing body surface were measured during the equipment operation under a rated load. Heat control was carried out from the beginning of a work shift at a 15 °C ambient temperature at an interval of 1 minute at a distance of 15 cm from the control points (Fig. 3, 4).

According to Blema's operational documentation, the heating temperature of the equipment bearing nodes is monitored at least once a month at the same control points no earlier than 60 minutes from the start of equipment operation using measurement equipment with a measurement error of ±2 °C. If a bearing node is in a difficult-to-reach place, measurements can be carried out immediately after the equipment operation is terminated. The heating temperature of the rolling bearings should not exceed the maximum value specified in the passport for a particular type of equipment.

The discrete values of the bearings' heating temperature over time, acquired by the method of direct measurements, were treated by the method of statistical analysis using the Microsoft Excel program. Based on the results of measurements of the surface temperature values of the bearing body, we calculated the values of the heating rate of a bearing ϑ_h using the Microsoft Excel program from the following formula:

$$\vartheta_h = \frac{\Delta T}{\Delta \tau}, \quad (1)$$

where $\Delta\tau$ is the time interval between temperature control measurements, min; $\Delta T = T_i - T_{(i-1)}$ is the absolute chain increment in the temperature control measurements, °C.

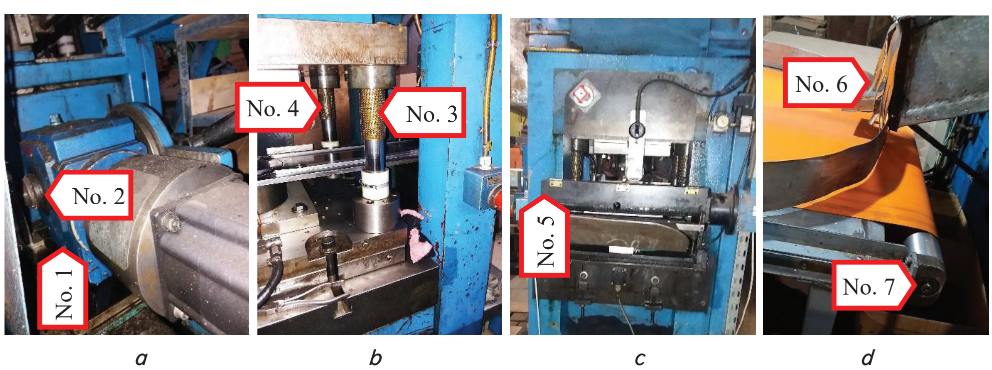
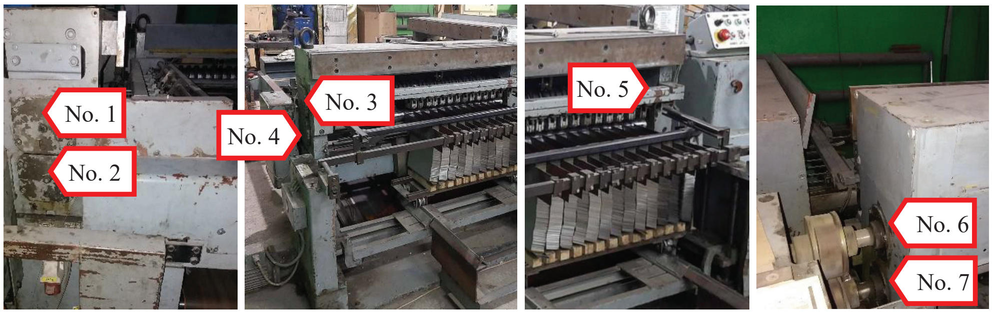


Fig. 3. Mechanical nodes of the press machine RKXD-63 No. 7308 made by Blema with the location of control points measuring the temperature of bearings: *a* – a worm reducer of the servo drive; *b* – a unit with ball guide nodes; *c* – a waste disposal mechanism; *d* – a belt transporter



a *b* *c* *d*

Fig. 4. Mechanical nodes of disk scissors ScStrEO 0.63x1120 made by VEB Blema Aue No. 54589 with the location of control points measuring the temperature of bearings: *a* – the left supports of the upper and lower disc knife of the longitudinal cut; *b* – left supports of the upper and lower disk knife for cross cut; *c* – the right support of the upper disk knife for cross cut; *d* – right supports of the upper and lower disk knife for longitudinal cut

In accordance with the hygienic requirements for food production, all measurements, including temperature, are recommended to be made by the contactless method.

The improved thermal method of technical control of bearing nodes employs the rate of heating, derived from the difference of discrete temperature values, as a diagnosing parameter. Therefore, for the obtained heating rate values, the error of the measuring equipment itself can be neglected because, at the temperature values difference, the error of the means of measuring equipment is also deducted. To improve the reliability of the measured temperature values, it is enough to use a measuring tool with a resolution higher than the rated error of measurements of ±2 °C, which is indicated in the operational documentation by Blema. These circumstances have made it possible to use in our experiments an affordable means of measuring equipment with a high resolution of temperature measurement of 0.1 °C. The specifications for the portable pyrometer GM 300, involved in all measurements, are given in Table 1.

Table 1

The characteristics of pyrometer GM 300

Measurement range, °C	from minus 50 to 300
Measurement error, %	1.5
Resolution, °C	0.1
Sighting index	12:1
Emission coefficient (fixed)	0.95

When measuring the temperature of an object using a pyrometer with a constant thermal radiation factor (*Econst*) and a thermal radiation factor (*ET*), one takes into consideration the correction (ΔT) at the given temperature of the object by calculating it from the following formula:

$$\Delta T=\Delta\cdot(Econst-ET). \qquad (2)$$

The error of the measured temperatures caused by errors in thermal radiation ratios of 1 %, at 20 °C and 30 °C, is zero ($\Delta=0$). Therefore, the correction ΔT was not taken into consideration when treating the temperature data.

The derived estimated values of the heating rate of rolling bearings were analyzed by a comparison method against the values of the intervals for the acceptable (3) and unacceptable (4) values based on the heating rate criterion over a time interval of the regular heating mode. The temporal regular heating interval of the bearing was determined by the method of regular thermal mode; to this end, a method of the least squares was applied for the logarithmic approximation of the heating temperature function by time. The moment when the chart line moves from a curved to a straight line is taken as a moment of the onset of a regular heating mode. Based on the results of the comparison, the technical condition of the rolling bearing was assessed according to the heating rate criterion under a regular heating mode.

If the heating rate value is within the interval of acceptable values:

$$\vartheta_h \leq 1.1\ °C/min, \qquad (3)$$

then the technical condition of the bearing is assessed to be efficient.

If the heating rate value is within the interval of unacceptable values:

$$\vartheta_h \geq 2\ °C/min, \qquad (4)$$

then the technical condition of the bearing is assessed as inoperable.

If the heating rate is within the following interval:

$$1.1<\vartheta_h<2\ °C/min, \qquad (5)$$

then there is a conditional probability of an undetected or false malfunction when assessing the technical condition of bearing nodes. In such a situation, the technical condition of bearings is assessed at control points by the standard thermal method comparing the measured temperature value with the normalized value of the acceptable heating temperature under the heating stabilization mode of the bearing node.

The above discrete heating rate values for criteria (3) to (5) were obtained empirically during the bench tests of mechanical reducers [18, 21–23] whose structure includes the ball radial and cylindrical roller single-row rolling bearings of the open and closed types.

5. Results of studying the heating of rolling bearings based on the parameters of temperature and heating rate

5. 1. Studying a change in the temperature and heating rate of rolling bearings

We have established the dependence of changes in the temperature and heating rate of the bearing nodes operating under the rated mode of the press machine RKXD-63 and ScStrEO disk scissors on the technical condition and operational modes of the rolling bearings.

Fig. 5 shows the results of controlling the heating temperature of the rolling bearings in the press machine RKXD-63 at control points No. 1–7 (Fig. 3).

The data were acquired under the following conditions: the operation of the press under a rated mode without stopping; the shaft rotation frequency is 85 rpm; for the conical bearing and ball separators, the loading is 14 kW; for the ball radical-supporting single-row bearings, the loading is 1.1 kW.

The assessment of the effect of the technical condition and the modes of operation of the RKXD-63 press machine's rolling bearings on a change in the heating temperature of the bearing nodes showed the following results. The dependence of the heating temperature on time for the RKXD-63 press machine's rolling bearings is non-linear (Fig. 5). The maximum intensity of the heating temperature increase is during the initial period up to minute 15, which corresponds to the mode of disordered heating. The intensive temperature increase stops at minute 25 when the heating stabilization mode begins. The determination factor magnitude is from $R=0.74$ to $R=0.97$, which indicates the reliability of the logarithmic approximation of charts of the function of the heating temperature of the RKXD-63 press machine's bearings by time.

Fig. 6 shows the results of controlling the heating temperature of the roller angular contact single-row rolling bearings of the disk scissors ScStrEO at control points No. 1–7 (Fig. 4). The data were acquired under the following conditions: the operation of the press machine lasting 33 minutes under a rated mode with a short stop on minutes 6 and 9; the shaft rotation frequency is 150 rpm; the loading is 1.2 kW.

The assessment of the effect of the technical condition and the modes of operation of the ScStrEO disk scissors' rolling bearings on a change in the heating temperature of the bearing nodes showed the following results. The dependence of the heating temperature on time for the roller angular contact single-row bearings of the ScStrEO disk scissors is non-linear (Fig. 6). The greatest temperature spikes occur between 0 and 15 minutes, which corresponds to the disordered heating regime. The heating temperature starts to stabilize from minute 25. The determination factor value of the logarithmic approximation is between 0.2 and 0.74, indicating the low reliability of the logarithmic approximation of charts of the function of the heating temperature of the ScStrEO disk scissor's bearings by time.

Based on the values of the bearings' heating temperature derived at control points No. 1–7 (Fig. 3, 4) of the RKXD-63 press machine (Fig. 5) and the ScStrEO disk scissors (Fig. 6), we determined the heating rate of the bearings according to formula (2).

Fig. 7 shows the calculation results in the form of a graphic dependence of heating rate on time for the RKXD-63 press machine's rolling bearings at control points No. 1–7 (Fig. 3).

Fig. 8 shows the calculation results in the form of a graphic dependence of the heating rate on time for the roller angular contact single-row rolling bearings in the ScStrEO disk scissors at control points No. 1–7 (Fig. 4).

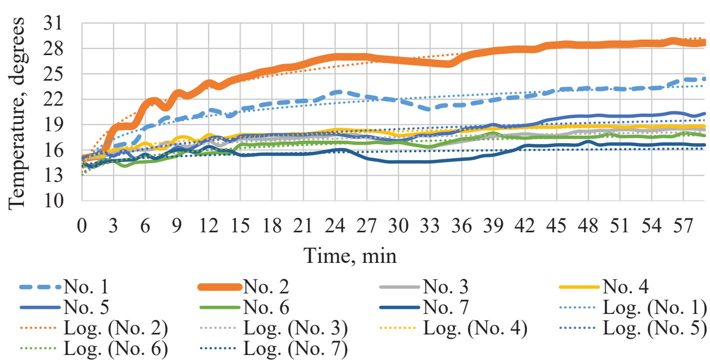


Fig. 5. Time-dependent change in the temperature of heating the rolling bearings in the press machine RKXD-63 at control points: No. 1 — the body of the reducer's carter; No. 2 — a conical bearing; No. 3 — a ball separator; No. 4 — a ball separator; No. 5 — a ball-angular contact single-row bearing; No. 6 — a ball angular contact single-row bearing; No. 7 — a ball angular contact single-row bearing

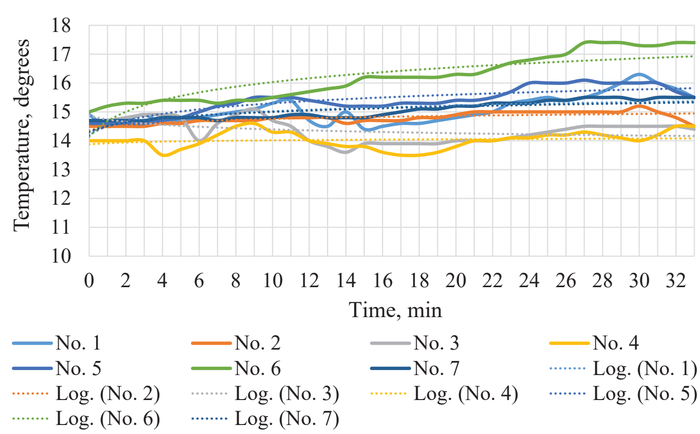


Fig. 6. Time-dependent change in the temperature of heating the roller angular contact single-row rolling bearings of the disk scissors ScStrEO at control points

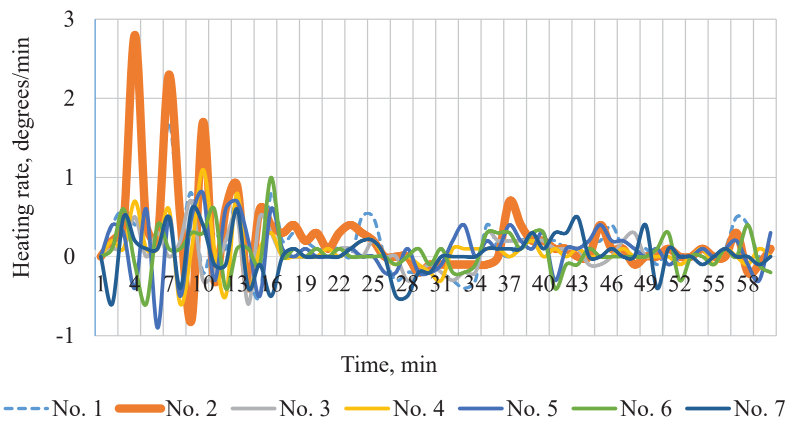


Fig. 7. Time-dependent change in the heating rate of the RKXD-63 press machine's bearings at control points: No. 1 – the body of the reducer's carter; No. 2 – a conical bearing; No. 3 – a ball separator; No. 4 – a ball separator; No. 5 – a ball angular contact single-row bearing; No. 6 – a ball angular contact single-row bearing; No. 7 – a ball angular contact single-row bearing

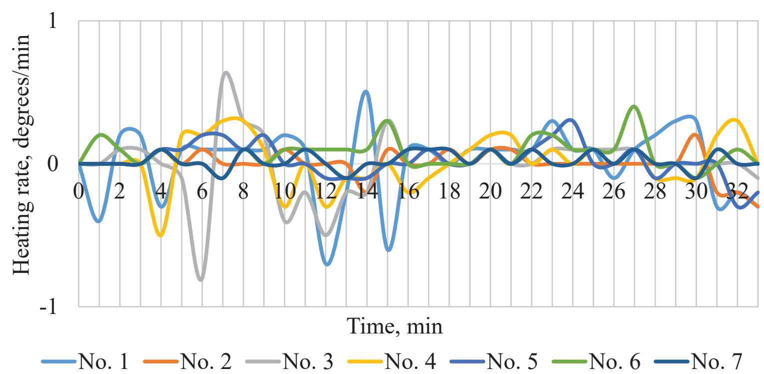


Fig. 8. Time-dependent change in the heating rate of the angular contact single-row rolling bearings of the ScStrEO disk scissors at control points

5. 2. Studying the pattern of change in the heating rate of rolling bearings

When testing the possibility of applying the empirical value of the criterion of the heating rate of mechanical reducers during bench tests as a diagnosing criterion for the operative assessment of the technical condition of rolling bearings of different types, the following results were obtained.

While controlling the heating of the rolling bearings, the dependence of the heating rate on time is nonlinear (Fig. 7, 8). The maximum amplitude of changes in the heating rate values is within a time interval from minutes 0 to 15 and is chaotic in character. After minute 15, the heating rate of the RKXD-63 press machine's rolling bearings did not exceed 0.7 °C/min (Fig. 8), and the heating rate of the ScStrEO disk scissor's bearings did not exceed 0.4 °C/min.

The resulting heating rate values of rolling bearings are within the interval of acceptable values (3) of the diagnosing criterion of the heating rate for mechanical reducers during bench tests, and the technical condition of the bearings is assessed as efficient.

5. 3. The basic principles of the thermal method of assessing the technical condition of rolling bearings based on the heating rate criterion

Based on the results of our study, it is possible to highlight the basic principles of the improved passive method of the thermal control of rolling bearings, which are:

– the introduction of an additional rated diagnosing criterion for the heating rate to promptly assess the operational technical condition of the rolling bearings;

– shifting the monitoring of rolling bearings over time: from the mode of stabilizing the heating to the mode of the regular heating of the bearing.

6. Discussion of results of studying the heating of rolling bearings based on the parameters of temperature and heating rate

An analysis of the heating temperature change in the rolling bearings of the bearing nodes in the RKXD-63 press machine (Fig. 5) and the ScStrEO disk scissors (Fig. 6) has revealed the following:

1) the bearings are in an efficient technical condition as the maximum value of the heating temperature under a stabilization mode does not exceed the allowable rated value: for ball bearings, 60 °C; for conical bearings, 70 °C. However, the technical condition can be assessed on the basis of the stabilized temperature not earlier than on minute 60;

2) at a rotation frequency of 85 rpm under a transmitted load of 14 kW, the functioning of the conical bearings of the worm reducer of the RKXD-63 press machine is accompanied by high heat output, ΔT_p=13.7 °C. The low heat output, from ΔT_p=2 °C to ΔT_p=5.3 °C, is characteristic of the ball angular contact single-row bearings under a load of 1.1 kW, as well as the ball separators that execute linear movement at a load of 14 kW;

3) with a rotational frequency of 150 rpm and a load of 1.2 kW, the ScStrEO disk scissor's bearings function with a low heat output from ΔT_s=0 °C to ΔT_s=2.4 °C. This significantly complicates determining the limits of the time interval that corresponds to a regular heating mode;

4) the highest intensity of variations in the values (amplitude jumps) of the heating temperature of the studied rolling bearings is observed in the interval of time from the beginning of control to minute 15. This is due to a strong dependence on the original state of the bearing node and corresponds to the stage of a disordered heating mode. From minute 15 to minute 25, the temperature dependence on time is exponential while the logarithmic trend line tends to a linear dependence. This is due to a change in the thermodynamic state of the control object and indicates the transition of the bearing heating stage to a regular heating mode. The heating regime begins its stabilization on minute 25. Minor temperature spikes in the temperature values are associated with a margin of error of the measuring device of 1.5 %;

5) short stops of the ScStrEO disk scissors on minutes 6 and 9, which were caused by technological necessity, led to a subsequent short-term reduction in the temperature of the bearing by a magnitude not exceeding the error of the measuring device. Therefore, the results of temperature measurements over the short periods of technological stops of the ScStrEO disk scissors can be neglected.

An analysis of the change in the heating rate of the rolling bearings in the bearing nodes of the RKXD-63 press machine (Fig. 7) and the ScStrEO disk scissors (Fig. 8) has revealed the following:

1) the largest value of the heating rate, ϑ_h=1 °C/min, under a regular heating mode, is demonstrated by the conical bearings of the RKXD-63 press machine's worm reducer, which operate under a load of 14 kW at a rotational frequency of 85 rpm;

2) the lowest value of the heating rate, ϑ_h=0.5 °C/min, under a regular heating mode, is demonstrated by the roller angular contact single-row rolling bearings, which function under a load of 1.2 kW at a rotation frequency of 150 rpm;

3) the maximum amplitude of fluctuations in the heating rate is observed in the interval of the time of disordered heating, which is not suitable for the evaluation of the technical condition of bearing nodes by a thermal method;

4) to assess the technical condition of bearing nodes using the improved thermal method based on the heating rate of the controlled rolling bearings, it is recommended to use a regular heating mode, which is within a time interval from minute 15 to minute 25 from the start of the equipment operation;

5) under a regular heating mode, regardless of the type of a bearing node and the operational conditions of a bearing, the heating rate value for all the types of rolling bearings under study in an efficient technical condition does not exceed 1 °C/min. The derived values correspond to the region of acceptable values based on the empirical criterion $\vartheta_h \leq 1.1$ °C/min of the heating rate of mechanical reducers, obtained in the bench tests under a mode of regular heating.

Thus, it can be argued that the empirically obtained values of the heating rate of mechanical reducers in bench tests for criteria (3) to (5) could be used as a diagnosing parameter for the operative assessment of the technical condition of ball radial and cylindrical roller single-row rolling bearings of the open and closed types under a regular heating mode. The advantage of the improved thermal control method is that the control measurements are carried out over a limited time interval from the beginning of the operation of technological equipment, from minute 15 to minute 25. If the measured heating rate value based on criterion (4) is exceeded, it could prevent the occurrence of an emergency of the equipment operated, which may arise due to inefficient bearing nodes.

The main stages of the thermal method of assessing the technical condition of rolling bearings according to the heating rate criterion are as follows:

1) measure the heating temperature of the rolling bearing;

2) calculate the heating rate of the rolling bearing under a regular heating mode;

3) compare the received values of the heating rate of the rolling bearing with the criterion for assessing the performance of the rolling bearing based on the heating rate under a regular heating mode;

4) assess the technical condition of the rolling bearing;

In the stage of a regular heating mode, there are peak heating rate values while the disordered and regular heating modes have short time intervals. Therefore, when controlling the technical condition of the rolling bearings according to the proposed method, it is necessary to take measurements of the heating temperature of the bearing with the discreteness of one minute.

In order to obtain a reliable assessment of the technical condition by using the improved method, it is recommended that the rolling bearings with an intensive mode of operation should be monitored, making it possible to determine the boundaries of the regular heating time interval and the beginning of the bearing entering a control mode. The equipment must function continuously at a constant ambient temperature, in order to avoid a decrease in the working temperature of the bearing, which can lead to a false malfunction when assessing the technical condition of the bearing nodes. This may be considered a limitation of this study as it indicates the necessary conditions for the reproduction of the results obtained and their application.

The regular heating mode interval is determined experimentally for each controlled rolling bearing. Therefore, in order to improve the reliability of the application of the improved thermal method of technical control by the criterion of the heating rate, additional research is needed to determine the boundaries of the time interval of the regular heating mode for rolling bearings, depending on their type, loading, and operating mode.

7. Conclusions

1. Our study has shown that under equal lubrication conditions, the thermal control results are most affected by the transmitted load and the type of a bearing. The results of control based on the heating rate under a regular heating mode are mainly influenced by the technical condition of the rolling bearing. Over an interval from minute 15 to minute 25 after the start of the operation, the studied ball radial and cylindrical roller single-row rolling bearings of the open and closed types are in a regular heating mode, suitable for the operative assessment of their technical condition.

2. We have empirically confirmed the possibility of applying a new diagnosing criterion of heating rate under a regular heating mode to assess the technical condition of the ball radial and cylindrical roller single-row rolling bearings of the open and closed type under a rated mode of operation of the press machine RKXD-63 and the disk scissors ScStrEO by the passive method of thermal control. The heating rate under a regular heating mode of the rolling bearing in an efficient technical condition corresponds to the inequality $\vartheta_h \leq 1.1$ °C/min.

3. The basic principles of the improved thermal method are the introduction of a diagnosing criterion of the heating rate and a shift in the time of operative control to the beginning of equipment operation. This could reduce the technological time for monitoring by 4 times, which would reduce the cost of equipment maintenance.

The greatest effect of the improved method application could be achieved with the introduction of the maintenance and repair system based on the actual technical condition of equipment.

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